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Comparison of Cl_2 and HCl Adsorption on Si(100)-(2x1)

by

Q.Gao, C.C. Cheng, P.J. Chen, W.J. Choyke and J.T. Yates, Jr.

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Department of Chemistry
University of Pittsburgh
Pittsburgh, PA 15260

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The chemisorption and reaction of Cl_2 and HCl on Si(100)-(2x1) have been studied using a variety of measurement methods. At 100K, both Cl_2 and HCl dissociatively chemisorb on the dangling bonds of Si(100). At saturation coverage, the surface concentration of Cl is about one Cl atom per Si atom while HCl can produce a Cl coverage only one fourth of that achieved with Cl_2. This is the first report of a self-site-blocking effect in adsorption on a semiconductor surface. HREEL spectra indicate that both Cl_2 and HCl adsorption at 100K give a monochloride surface species with a Si-Cl stretching frequency of ~550-600 cm^{-1}. Digital ESDIAD measurements reveal that the Si-Cl bond angle for the monochloride from both Cl_2 and HCl adsorption is oriented on the vertical plane containing the Si-Si dimer bond and is inclined from the surface normal. The etching products of Si(100) by Cl_2 at elevated temperatures are $SiCl_2$ at ~ 800K and a small amount of $SiCl_4$ at ~ 500K. For HCl, the only observed etching product is $SiCl_2$.

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Q. Gao, C. C. Cheng, P. J. Chen*, W. J. Choyke* and

J. T. Yates, Jr.

Surface Science Center
Department of Chemistry
University of Pittsburgh
Pittsburgh, PA 15260
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Q. Gao, C. C. Cheng, P. J. Chen*, W. J. Choyke* and

J. T. Yates, Jr.

Surface Science Center
Department of Chemistry
University of Pittsburgh
Pittsburgh, PA 15260

and
*Department of Physics
University of Pittsburgh
Pittsburgh, PA 15260.

Abstract

The chemisorption and reaction of Cl_2 and HCl on Si(100)-(2x1) have been studied using a variety of measurement methods. At 100K, both Cl_2 and HCl dissociatively chemisorb on the dangling bonds of Si(100). At saturation coverage, the surface concentration of Cl is about one Cl atom per Si atom while HCl can produce a Cl coverage only one fourth of that achieved with Cl_2. This is the first report of a self-site-blocking effect in adsorption on a semiconductor surface. HREEL spectra indicate that both Cl_2 and HCl adsorption at 100K give a monochloride surface species with a Si-Cl stretching frequency of ~550-600 cm^{-1}. Digital ESDIAD measurements reveal that the Si-Cl bond angle for the monochloride from both Cl_2 and HCl adsorption is oriented on the vertical plane containing the Si-Si dimer bond and is inclined from

the surface normal. The etching products of Si(100) by Cl_2 at elevated temperatures are $SiCl_2$ at ~ 800K and a small amount of $SiCl_4$ at ~ 500K. For HCl, the only observed etching product is $SiCl_2$.

1. Introduction

It is important to understand the basic chemistry of chlorine chemisorption and reaction on semiconductor surfaces, since Cl-containing molecules, such as SiH_2Cl_2 [1] and $GaCl_3$ [2], have been used as precursor molecules for atomic layer epitaxy processes, and Cl_2 molecules have been used in the ion [3-5] or photon assisted etching [6-8] process.

In this report, the saturation coverage and vibrational spectrum of Cl(a) derived from Cl_2 and HCl adsorption are compared on Si(100). In addition, Cl^+ ESDIAD patterns from Si-Cl bonds on Si(100) are reported, giving information about the Si-Cl bond direction.

2. Experimental

Experiments were carried out in two UHV chambers. The first one was equipped with a digital ESDIAD/LEED (electron stimulated desorption ion angular distribution/low energy electron diffraction) apparatus, an Auger electron spectroscopy (AES), a quadrupole mass spectrometer (QMS) for line-of-sight temperature programmed desorption (TPD), and an additional QMS for ion mass analysis in ESD. The second UHV chamber housed a high resolution electron energy loss spectrometer (HREELS), LEED, AES and a QMS for TPD. The primary beam energy used for HREELS study was 4.2 eV

and the full width at half maximum (FWHM) of the elastic beam was about 65 cm^{-1} . Flux-calibrated microcapillary-collimated gas dosers [9,10] were used in both chambers for control of the Cl_2 or HCl exposure. The Si(100) single crystal was cleaned by Ar^+ sputtering and subsequent annealing at 1173K. The crystal temperature was measured by a chromel-constantan thermocouple enclosed in a Ta-foil envelope which was inserted into a slot on the crystal edge [9].

3. Results and Discussion

3.1. Adsorption of Cl_2 and HCl

The saturation coverage of the chlorine layer derived from the adsorption of Cl_2 and HCl was measured. Figure 1 is an Auger measurement of the development of the Cl(a) coverage using the two molecules as a function of exposure. It is noticed that at about $3x10^{14}$ molecules/cm^2 exposure, both the Cl_2 and HCl adsorption rate has dramatically decreased. The reduction of the adsorption rate for Cl_2 is due to the lack of available surface dangling bonds since all of them are nearly used up for the chemisorption [11]. The perfect Si(100)-(2x1) surface exposes $6.8x10^{14}$ dangling bonds/cm^2. Thus, at a Cl_2 exposure near ~$3x10^{14}$ Cl_2/cm^2, saturation of the dangling bonds is expected to occur (near the break point in the curve) assuming a sticking

probability of unity in the initial adsorption region. Beyond the break point at ~$3x10^{14}$ Cl_2/cm^2, the coverage continues to rise slowly as the Cl_2 exposure is increased. For the same exposure (~$3x10^{14}$ molecules/cm^2), the saturation effect is also observed for HCl adsorption. The surface Cl coverage from HCl adsorption is only about one-fourth of that achieved by Cl_2 adsorption, as obtained from the Cl/Si AES intensity ratio in Figure 1. The Cl_2 molecules are composed of two Cl atoms which give a Cl coverage of nearly one Cl atom per dangling bond at the break point. In comparison, HCl is composed of one Cl atom and one H atom. If the surface dangling bonds were all occupied by H(a) and Cl(a) from HCl adsorption, a Cl surface coverage of about 0.5 would be expected. However, at the break point only about one fourth of the surface dangling bonds are occupied by Cl from HCl adsorption at 100K. The surface has one half of the dangling bonds which are not accessible for HCl adsorption. Furthermore, after a saturation exposure of HCl is achieved, exposure of this prepared surface to Cl_2 leads to increased Cl coverages as measured by AES, indicating that the dangling bonds inaccessible for HCl adsorption are active for Cl_2 adsorption. Thus, the HCl adsorption on Si(100) is a self-site-blocking process. To our knowledge, this is the first report of such a self-site-blocking adsorption process on a semiconductor surface. The immediate conclusion from this result is that HCl will be a less effective etchant than

Cl_2 due to its limited surface coverage on Si(100). The nature of this self-sit-blocking adsorption phenomena is not well understood at present.

3.2. Vibrational Studies of Cl_2 and HCl Adsorption

Deeper insight into the chlorine surface chemistry can be obtained from the vibrational characterization of the surface species formed during the chemisorption and reaction. Figure 2 shows the vibrational spectra after Cl_2 and HCl adsorption on Si(100)-(2x1) at 100K. It is noticed that only one strong Si-Cl stretching mode, ν(SiCl), is observed at ~600 cm^{-1} and at ~550 cm^{-1} for Cl_2 and HCl adsorption, respectively [12]. For HCl adsorption, an additional vibrational feature is observed at ~2120 cm^{-1} (figure 2b) which is due to the SiH stretching mode [13]. The lack of a HCl stretching mode near ~3000 cm^{-1} [14] and the appearance of ν(SiCl) and ν(SiH) modes indicate that HCl is dissociated upon adsorption at 100K.

The vibrational spectra (Figure 2) indicate that higher surface chloride species, such as $SiCl_2$(a), $SiCl_3$(a) or $SiCl_4$(a), are not observed following either Cl_2 or HCl adsorption at 100K. These chlorides should exhibit an asymmetric stretching mode [ν_a(SiCl)~533-617 cm^{-1}], and a symmetric stretching mode [ν_s(SiCl) ~376-465 cm^{-1}]; in addition a bending vibrational mode should be present [d (Si-Cl)~164-261 cm^{-1}] [12a-e]. There is no prominent

evidence for these modes in the spectra observed. This is consistent with the dissociative adsorption of HCl and Cl_2 forming surface monochloride species. For Cl_2 adsorption at 100K, the mode at 295 cm^{-1} has been assigned to a Si_2Cl stretching mode for a bridge-bonded Cl species, a minority species [15].

3.3. ESDIAD Studies of Si-Cl Bonding on Si(100)

The ESDIAD method has been employed to study the bonding of Cl(a) to Si(100) using both Cl_2 and HCl as adsorbates. In this method, the adsorbed layer is bombarded by electrons (V_e=120 eV in this case) and the angular distribution of Cl^+ ions is detected by a digital technique. The ejection angle of the Cl^+ ions is determined primarily by the orientation of the Si-Cl bond being broken [16-18] in the electronic excitation. This angle is modified by final state effects involving the Cl^+ interaction with its image charge as well as by Cl^+ reneutralization near the surface [19-20].

The surface monochloride species produced from HCl or Cl_2 adsorption give four off-normal Cl^+ emission beams observed from the ESDIAD measurements, shown in Figure 3. The Cl^+ ions are ejected in planes perpendicular to the crystal surface but parallel to the surface Si-Si dimer bond axes, as confirmed from the comparison of the ESDIAD pattern with the (2x1) LEED patterns of the substrate

surface. Slight misalignment of the Si single crystal from the (100) direction results in a stepped surface with Si-Si dimer rows oriented alternately in orthogonal directions, forming (1x2) and (2x1) domains of reconstructed surface. The inclined Cl bonds of the surface monochloride species from both types of domains produce the four off-normal Cl^+ ion beams. A single domain surface would give two off-normal Cl^+ ion beams with the opposite polar angle with respect to the surface normal.

3.4. Thermal Desorption Studies

The thermally activated etching reaction was investigated by TPD measurements. The results (Figure 4) indicate that Cl(a) from both Cl_2 and HCl chemisorption etches the Si(100) surface, producing $SiCl_2(g)$ with a desorption peak temperature at ~820K for the Cl_2/Si(100) system and at 840K for the HCl/Si(100) system. A small amount of $SiCl_4$ desorption (monitored by its major mass spectrometer cracking product, $SiCl_3^+$, m/e=133 amu) is also observed for the Cl_2/Si(100) system at monolayer or higher exposures. This is consistent with the previous Cl_2/Si(100) TPD results [6, 21]. These measurements indicate that $SiCl_2$ is the main etching product for both Cl_2 and HCl adsorption, and that the etching process involving $SiCl_2$ occurs near 840K. Species such as SiH_4 (monitoring m/e=30 amu) or SiH_3Cl (monitoring m/e=31 amu), SiH_2Cl_2 (monitoring

m/e=99 amu) and $SiHCl_3$ (monitoring m/e=133 amu) were not detected in desorption, showing that the surface hydrogen atom was not involved in the etching process when HCl was employed.

An effort was made for the Cl_2/Si(100) system to observe by HREELS whether the $SiCl_2$(a) species could be detected by raising the crystal temperature to ~850K, followed by cooling to 100K. The HREEL spectrum remained essentially the same, exhibiting a single Si-Cl stretching mode of the surface monochloride shown in Figure 2a with a reduced intensity and a slight reduced frequency (to about 570 cm^{-1}) due to the reduction of surface chlorine coverage. Thus, $SiCl_2$(a) formation is probably the rate determining step for $SiCl_2$(g) liberation.

4. Conclusions

The following conclusions may be made from these studies of Cl_2 and HCl chemisorption on Si(100)-(2x1).

(1). Dissociative adsorption of both Cl_2 and HCl occurs on Si(100)-(2x1) at 100K. The vibrational spectra of the species produced from Cl_2 and HCl adsorption indicate that Si-Cl bonds are formed in both cases. For HCl chemisorption, the Si-H bond is also observed.

(2). For Cl_2 adsorption, about one Cl atom/Si dangling bond is produced at saturation

coverage. In addition, the saturation coverage of chlorine from Cl_2 adsorption is ~4 times greater than that from HCl adsorption. This result implies that HCl adsorption involves an adsorption site exclusion process, where neither H(a) or Cl(a) species can populate one-half of the dangling bond sites exposed on Si(100)-(2x1).

(3). ESDIAD studies indicate that the Si-Cl bonds are inclined away from the surface normal direction along perpendicular planes containing the Si-Si dimer bonds.

(4). $SiCl_2$ is the main etching product observed from thermal desorption studies of Cl_2 and HCl on Si(100). It desorbs near 800K in both cases. HREELS studies indicate that $SiCl_2$(a) is not produced in measurable amount on heating the surface. This indicates that the rate determining step for $SiCl_2$(g) desorption is the conversion of SiCl(a) species to $SiCl_2$(a) species which then desorb.

5. Acknowledgments

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References

1. J. Nichizawza, K. Aoki and S. Suzuki, J. Crystal Growth 99 (1990) 502.
2. R. Kobayashi, K. Ishikawa, S. Narahara and F. Hasegawa, 2nd International Symposium on Atomic Layer Epitaxy, Raleigh, N. C., 1992
3. M. C. Chuang and J. E. Coburn, J. Vac. Sci. Technol. A8 (1990) 1969.
4. J. O. Chinn and E. D. Wolf, J. Vac. Sci. Technol., B3 (1985) 410.
5. P. C. Zalm, A. W. Kolfschoten, F. H. M. Sanders and P. Vischer, Nucl. Instru. Meth., B18 (1987) 625.
6. R. B. Jackman, H. Ebert and J. S. Foord, Surf. Sci., 176 (1986) 183.
7. W. Sesselmann and T. J. Chuang, J. Vac. Sci. Technol., B3 (1985) 1507.
8. W. Sesselmann, E. Hudeczek and F. Bachmann, J. Vac. Sci. Technol., B7 (1989) 1284.
9. M. J. Bozack, L. Muehlhoff, J. N. Russell, Jr., W. J. Choyke, and J. T. Yates, Jr., J. Vac. Sci. Technol. A5, (1987),1.
10. A. Winkler and J. T. Yates, Jr., J. Vac. Sci. and Technol. A6(5) (1988) 2929.
11. Cross calibrations of surface Cl coverage from Cl_2 adsorption on Si(100) with the saturation coverage of monohydride from atomic hydrogen adsorption indicate

that the surface Cl coverage is about 0.9 at the break point of the Cl_2 AES uptake curve.

12. (a) K. Nakamoto, in "Infrared Spectra of Inorganic and Coordination Compounds", 4th ed., New York, John Wiley & Sons, Inc., 1986, p. 132.
    (b) M. C. Tobin, J. Am. Chem. Soc., 75 (1953)1788
    (c) K. Shimizu and H. Murata, Bull. Chem. Soc., Japan, 32 (1959) 46.
    (d) L. Burnelle and J. Duchesne, J. Chem. Phys. 20 (1952) 1324.
    (e) J. Lanne, Spectrochimica Acta 26A (1970) 517.
13. (a) H. Wagner, R. Butz, U. Backes and D. Bruchmann, Solid State Commun., 38 (1981) 1155;(b) Y. J. Chabal, Surf. Sci. Reports, 8 (1988) 211. (c) H. Ibach, H. Wagner and D. Bruchmann, Solid State Commun., 42 (1982) 457.
14. K. Nakamoto, in "Infrared Spectra of Inorganic and Coordination Compounds", 4th ed. New York, John Wiley & Sons, Inc., 1986, p. 101.
15. Q. Gao, C. C. Cheng, P. J. Chen, W. J. Choyke and J. T. Yates, Jr., manuscripts in preparation.
16. R. D. Ramsier and J. T. Yates, Jr., Surf. Sci. Reports, 12 (1991) 243.
17. T. E. Madey, Science, 234 (1986) 316.
18. J. T. Yates, Jr., M. D. Alvey, M. J. Dresser, M. A. Henderson, M. Kiskinova, R. D. Ramsier and A. Szabo, Science, 225 (1992) 1397.

19. Z. Miskovic, J. Vukanic and T. E. Madey, Surf. Sci. 169 (1986) 405.

20. D. P. Woodruff, Surf. Sci. 124 (1983) 320.

21. C. C. Cheng, S. R. Lucas, H. Gutleben, W. J. Choyke, and J. T. Yates, Jr., J. Am. Chem. Soc., 114 (1992) 1249, and unpublished TPD results for Cl_2/Si(100).

Figure Captions:

Fig. 1. Rate of Cl coverage increase for Cl_2 and HCl adsorption on Si(100)-(2x1) at 100K using Auger Spectroscopy. V_e = 2.0 kV.

Fig. 2. HREEL spectra of Cl_2 and HCl adsorption on Si(100)-(2x1) at 100K: (a) Cl_2 exposure=7.4×10^{14} molecules/cm^2; (b) HCl exposure=8.7×10^{14} molecules/cm^2. Contour profiles are plotted by an increment of 1/6 of their peak maxima.

Fig. 3. Cl^+ ESDIAD patterns of (a) Cl_2 (after annealing to 673K to get sharp monochloride pattern), and (b) HCl (120K adsorption). Near saturation coverages were achieved for Cl_2 and HCl adsorption prior to these measurements. V_e=120 eV.

Fig. 4. Temperature programmed desorption from layers produced from Cl_2 and HCl adsorption to saturation coverage on Si(100)-(2x1). Heating rate is ~3.6K/sec.

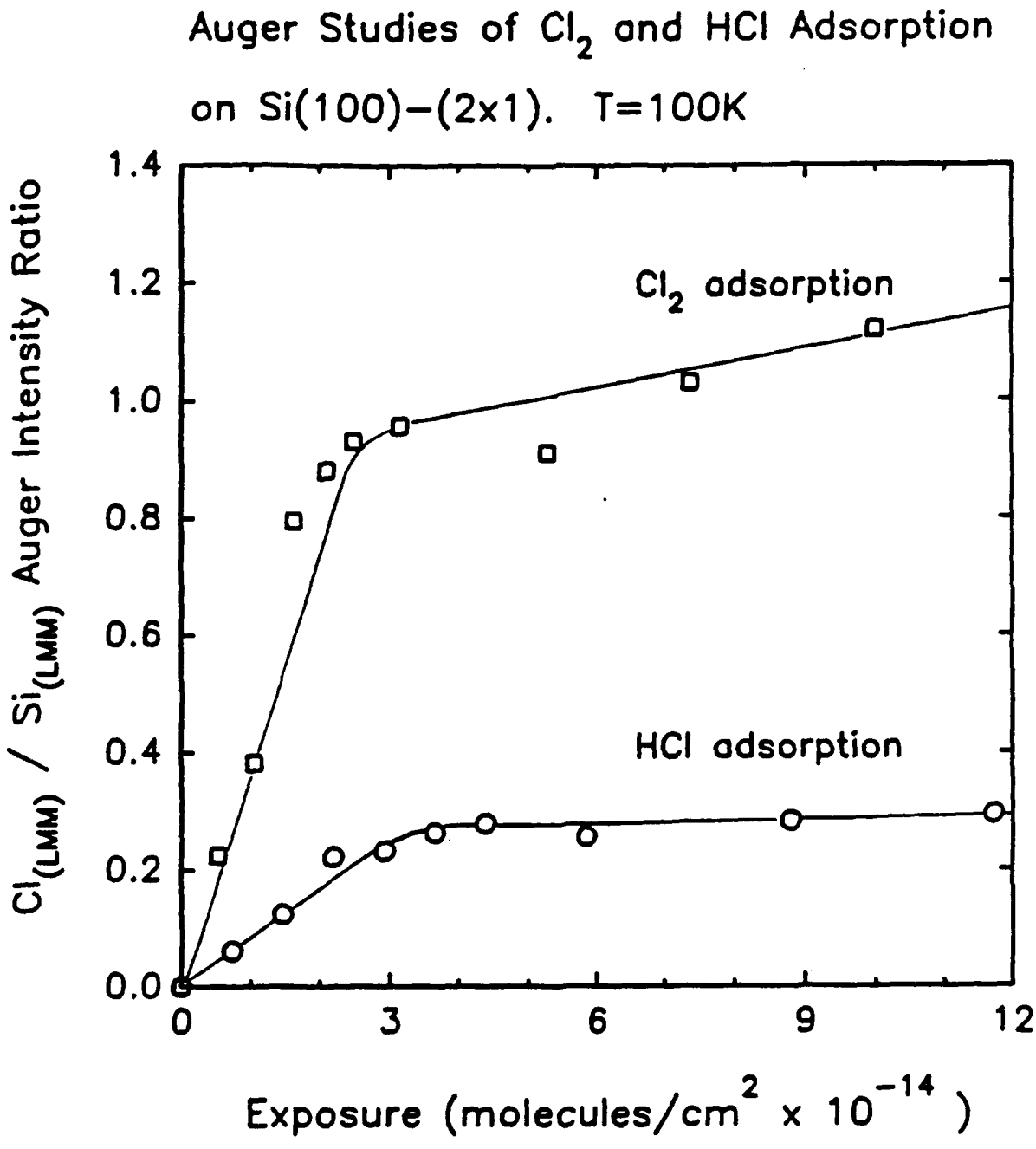

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Figure 1

Comparison of the Vibrational Spectra for Cl_2 and HCl Adsorption on Si(100)

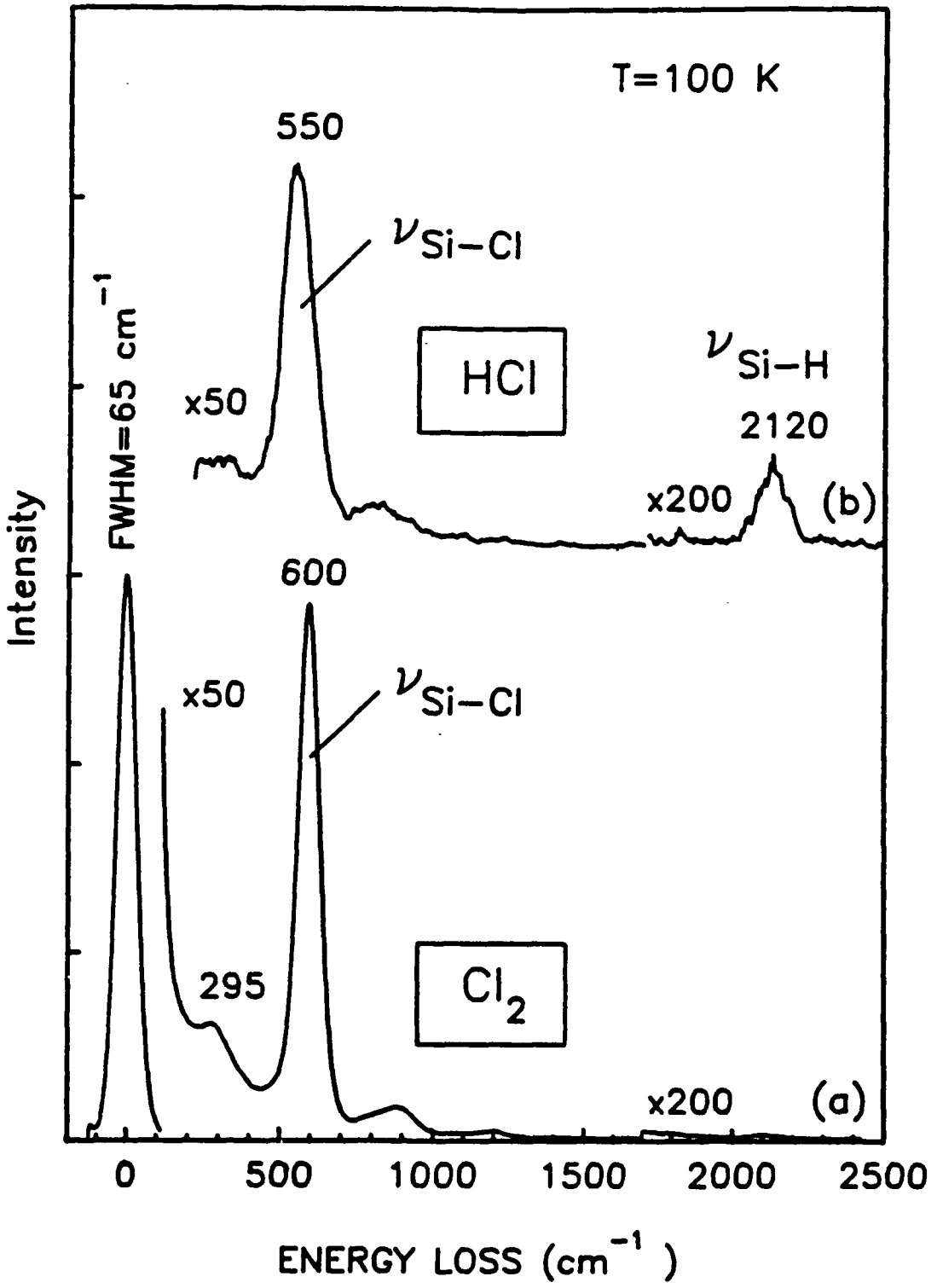

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Figure 2

Cl^+ ESDIAD Studies for Cl_2 and HCl Adsorbates on Si(100)-(2×1)

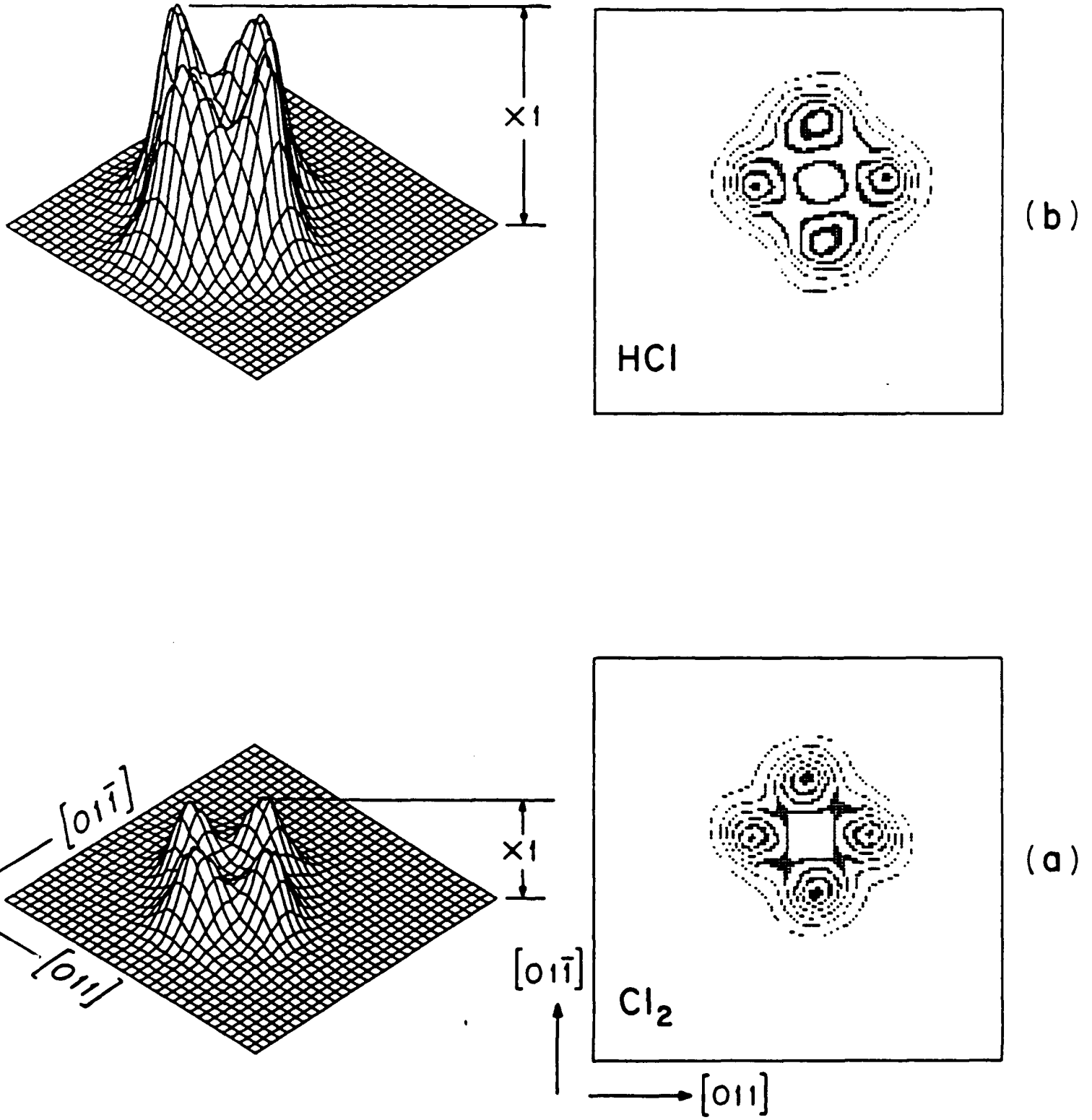

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Figure 3

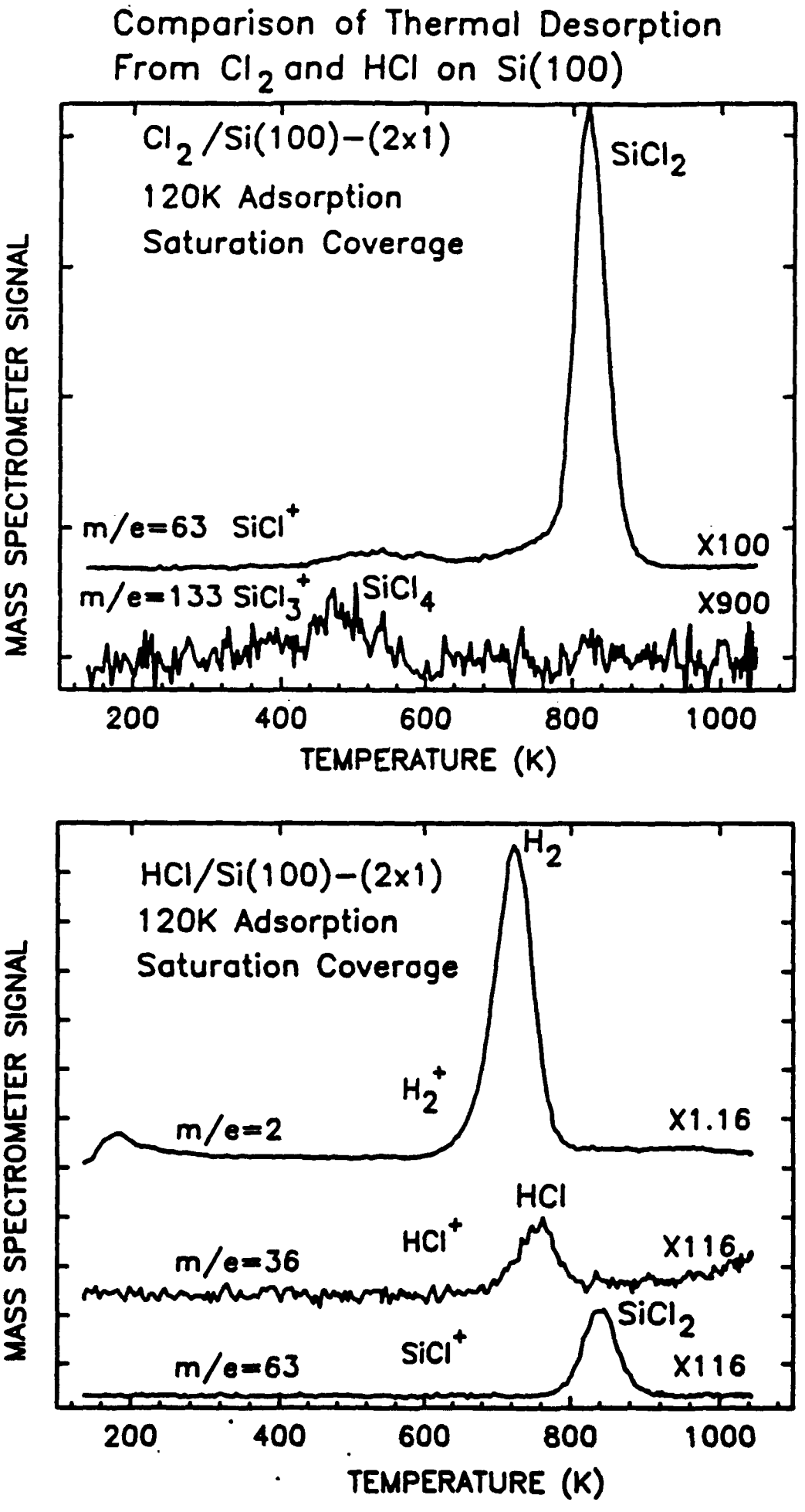

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Figure 4

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N.C.S.U.; Box
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ONR, Code 1114
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FAXes (703) 696-2611/3945/5383
e-mail: pazik@ocnr-hq.navy.mil
pazik%estd.decnet@ccf.nrl.navy.mil

Prof. J. T. Yates, Jr. 1
Dept. of Chemistry
Surface Science Ctr.
University of Pittsburgh
Pittsburgh, PA 15260
Tel: (412) 624-8320
FAX: (412) 624-8552
e-mail: yates@vms.cis.pitt.edu

Robert J. Markunas, R.A. Rudder 1
Research Triangle Institute; Box 12194
Research Triangle Park, NC 27709-2194
Tel: (919) 541-6153
FAX: (919) 541-6515
e-mail: rjmk@rti.rti.org

Professor Mark P. D'Evelyn 1
William Marsh Rice University
Dept. of Chemistry
P.O. Box 1892
Houston, TX 77251
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